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Guiding principles in developing the South African approach to durability index testing of concrete

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ABSTRACT

Focused thinking on the possibility of early-age testing of concrete for long-term durability started in earnest during the late 1980's in South Africa. Through sustained research, development and trial implementation on construction projects, three durability index tests have emerged, two of which have been adopted as national standard test methods for concrete construction, the remaining one being prepared as a national standard. In this paper we review the foundational principles that directed the development of these durability index tests, with a view to assessing the appropriateness and relevance of these guiding principles to modern concretes. The last 30 years have seen significant changes in concrete-making materials and concreting practice, as well as in our understanding of the behaviour of concrete in aggressive environments. This paper considers the role and place of DI testing in the broad framework of our understanding of the deterioration of concrete in aggressive environments and the ways in which we can ensure improved durability of concrete structures. While acknowledging that the important questions about index testing and long-term durability are not settled, this paper argues that the foundational principles and initial assumptions are largely valid. The paper also points to the challenges presented by advances in concrete materials technology to the ability for DI testing to reliably indicate long-term durability of these concreting materials.

Keywords: Concrete; Durability; Framework; Testing; Quality; Design

1.0 INTRODUCTION

Recognition of the susceptibility of Portland cement-based concrete to deterioration by aggressive agents in the environment emerged soon after the use of concrete became generalised as a construction material in the late 1800's and early 1900's. Over the years, empirically observed instances of concrete deterioration were studied and increasingly reliable explanations for the causes and mechanisms for particular forms of deterioration were found – and continue to be developed.

Alongside this improving understanding of the mechanisms of deterioration of both concrete and reinforced concrete, was a growing recognition of the need to develop a more systematic response to the durability of concrete in a manner that acknowledges the reality of the deterioration mechanisms and provides evidence-based engineering responses to ensure adequate service life and reduced maintenance costs of concrete infrastructure. Global research interest in the development of a systematic approach to ensuring the durability of concrete – as distinct from deterioration and rehabilitation of concrete – grew significantly in the 1980's, mainly driven by concerns about the increasing costs of repair and rehabilitation of concrete infrastructure that showed signs of early deterioration. In this context, the concerned voices were mainly those of the owners of large stocks of concrete infrastructure, for the obvious reason of loss of infrastructure asset value. However, the cement and concrete industries also were concerned about the negative effects of early deterioration on the market acceptability of concrete as a structural material.

At this stage, researchers in South Africa had already made significant contributions to understanding of concrete deterioration in areas such as sewer deterioration, alkali-silica reaction, the structural effects of deterioration, nuclear radiation effects on concrete, and the problem of shrinking aggregates in concrete (as examples, see: Kelly & Krüger, 1996; Oberholster, 1983; Blight, *et al.*, Kaplan, 1989). Following the global trend in this area, considerations of concrete deterioration naturally evolved into discussions on the need to assure better durability of concrete structures in South Africa. These discussions started in earnest during the late 1980's, when the need for performance-based durability specifications was recognised as an important contributor to addressing the problem. In one such discussion, Bentur (1992) pointed to the problem of the disconnect between the constructor's responsibility for the very early age performance of the structure and the owners' responsibility for its long-term performance, when deterioration normally manifests, without the owner having the necessary instruments for ensuring long-term durability at the time of construction.

Drawing on these early discussions, this paper discusses the foundational principles and the evolution of the strategic approach that were used to guide the development of concrete durability index testing in South Africa. The paper presents the broad framework that was developed in the early phase of our research that linked the different aspects of concrete durability, with a view to ensuring internal coherence and consistency in the different areas of concrete durability research and application, as well as the development of the present national specification for durability index testing. Research test results related to the different aspects of development of the test methods are also presented so as to illustrating the approach that was used to ensure general acceptability of the test methods by clients, designers, materials suppliers and constructors in the concrete industry.

2.0 A FRAMEWORK FOR DURABILITY RESEARCH AND DEVELOPMENT

During the early discussions on the development of our approach to research aimed at enhancing the resistance of concrete structures to deterioration, it was acknowledged that durability is not an inherent material property of concrete, in the way that strength or elastic stiffness are inherent material properties. This is simply because durability, as a concept, incorporates concrete as a _materials system_ in interaction with an _exposure environment_ that is variable in its degree of aggressiveness to the concrete.

It was this acknowledgement of "durability" as a concept that led to the early development of a framework that would both integrate and bring coherence to the different aspects of our research in the general field of concrete durability. Figure 1 shows the framework that was adopted for our research in concrete durability. This is an adapted version of the framework that was first presented by Alexander and Ballim (1993) and is intended to identify the interrelationships between aspects like index testing, short- and long-term deterioration tests, structural performance, deterioration mechanisms, environmental classification, quality assurance and structural life-cycle performance

The framework shown in Fig. 1 takes as its starting point the need to characterise or index the concrete, as a material system, in relation to its ability to resist the deteriorating effects of the environment of exposure. This indexing is particularly important for the cover zone of the concrete structure, considered as the first line of defence in protecting the underlying structural concrete. The index must also be a reproducible measure that can be reliably referenced to a performance scale that would indicate the likely durability of the concrete.

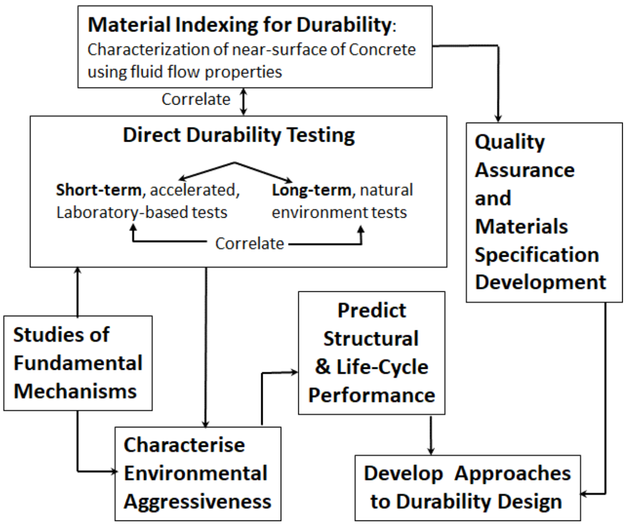


Fig. 1. Guiding framework for durability research and development in the South African context (adapted from Alexander and Ballim, 1993).

The durability index measures must then be correlated with the results of direct durability testing, both long-term tests in natural aggressive environments as well as accelerated laboratory-based aggressive environments. This allows the durability index performance scale to be developed, from which a quality assurance and concrete performance specification can be developed, with durability indexes as early-age control parameters for the quality of construction.

A deeper understanding of the fundamental mechanisms of concrete deterioration in different aggressive environments is also required to better understand the interactions between concrete and its environment and to characterise the nature and degree of aggressiveness of the environmental conditions. This is essential in order to develop models that are able to predict the structural and life-cycle performance of the concrete in its environment.

The primary objective of the framework approach to durability and deterioration of concrete is to develop increasingly reliable approaches to durability design of concrete structures. The understandings that emerge from the research must give greater meaning to the use-value of the durability indexes in a manner that positively influences specifications and structural design codes, and so provides designers and constructors of concrete infrastructure with the instruments needed to ensure improved durability of our structures.

The sections which follow highlight the guiding principles and strategic considerations that influenced the development of research in each of the components of the framework shown in Fig. 1. Where applicable, these sections also indicate examples of the research findings that have emerged from the work undertaken by the research teams over the past 28 years.

3.0 EXPLORING DIFFERENT ASPECTS OF THE DURABILITY FRAMEWORK

3.1 Developing the Durability Index Tests

Since durability is not an inherent material property of concrete, it follows that any test that measures a physical property of concrete with a view to assessing its durability can, at best, only be an indicator or "index" of the *likely* durability of the material. This is not unusual in the field of concrete technology, and it can easily be argued that a compressive strength test on a sample of concrete is also an index of the likely performance of the material under the complex processing variables and stress state of the (nominally) same concrete in an actual structure.

It was not very long ago that many specifications for concrete considered compressive strength as a sufficient indicator of concrete durability (as examples, see SANS, 2000; ACI, 2005). Indeed, some specifications still do so tacitly through minimum compressive strength limits. The weakness of a compressive strength test as indicator of durability lies primarily in its inability to account for concrete processing variables such as *in situ* compaction and curing. The need for a durability test that is sufficiently sensitive to such variables led to what is now generally accepted as a requirement to measure the fluid transport properties of concrete in one form or another. Andrade and Izquierdo (2005)] proposed the use of fluid-flow indicators for controlling the important durability parameters of concrete. Baroghel-Bouny (2002, 2004) considered several 'durability indicators' to use for referencing and controlling a wide range of forms of concrete deterioration.

An important requirement of the durability index test is that it be conducted on the concrete at a relatively early age during the construction period, but be able to be used to make statements about the long-term service performance of the concrete. In many ways, this is similar to the demands we make of a 28-day compressive strength test on a small sample of the concrete.

An important consideration in the development of fluid flow test parameters for concrete as indicators of potential durability was the need to account for both the materials used to make the concrete and the way in which these materials were mixed and processed into the final form of concrete in the structure. The test therefore had to be sufficiently sensitive to account for changes in concrete materials parameters such as binder type, concrete mixture design, w/c ratio and admixture effects as well as construction processing parameters such as mixing, compaction and - most importantly - curing.

A number of test methods have been developed to provide index measures of the fluid flow properties of the surface of concrete (Concrete Society, 1987; Kelham, 1988; Schonlin and Hilsdorf, 1988). While all the proposed approaches and test methods accepted the principle that the *in situ* concrete was to be tested, some test methods required that the test be conducted on the actual structure while others required that a sample of the concrete from the structure be extracted, brought into the laboratory for conditioning and then subjected to a fluid flow test. This debate has not fully been settled in the international research community and both approaches have their share of supporters.

This research work, which eventually developed three South African durability index tests for concrete, has its origins in a research project started in 1989. In this research work, it was decided to adopt the approach of extracting samples from the concrete structure for laboratory conditioning before testing, for a number of reasons: that control of the moisture content of the concrete in situ was a major obstacle; that the macro flow paths for a fluid transport test are difficult to predict for in situ conditions; and because it was realised that contractors would challenge any procedure where rigorous sample preparation and testing was not done. Further, there was an urgent need to address the problem in South Africa and this laboratory pre-conditioning approach offered the possibility of a reasonable time horizon within which to develop the tests for practical use.

In the development of these test methods, the further requirements were that they be relatively easy to perform in a construction site laboratory, that the equipment be of low cost and easy to manufacture and that test sample size be small so as to minimise the possible negative aesthetic effects of sample removal on the concrete structure.

The research, conducted by the collaborating research teams at the University of the Witwatersrand and the University of Cape Town, initially developed the oxygen permeability and water sorptivity tests (Ballim, 1993a,b) and later, the chloride conductivity test (Streicher and Alexander, 1995). The basic configuration and principles of operation are illustrated in Figs. 2(a) to 2(c). While the operational principles have remained the same, the test methods and equipment have undergone significant refinement and improvement over the years thanks to better understanding of the influencing variables through the research work of many postgraduate students who have worked in the two research teams.

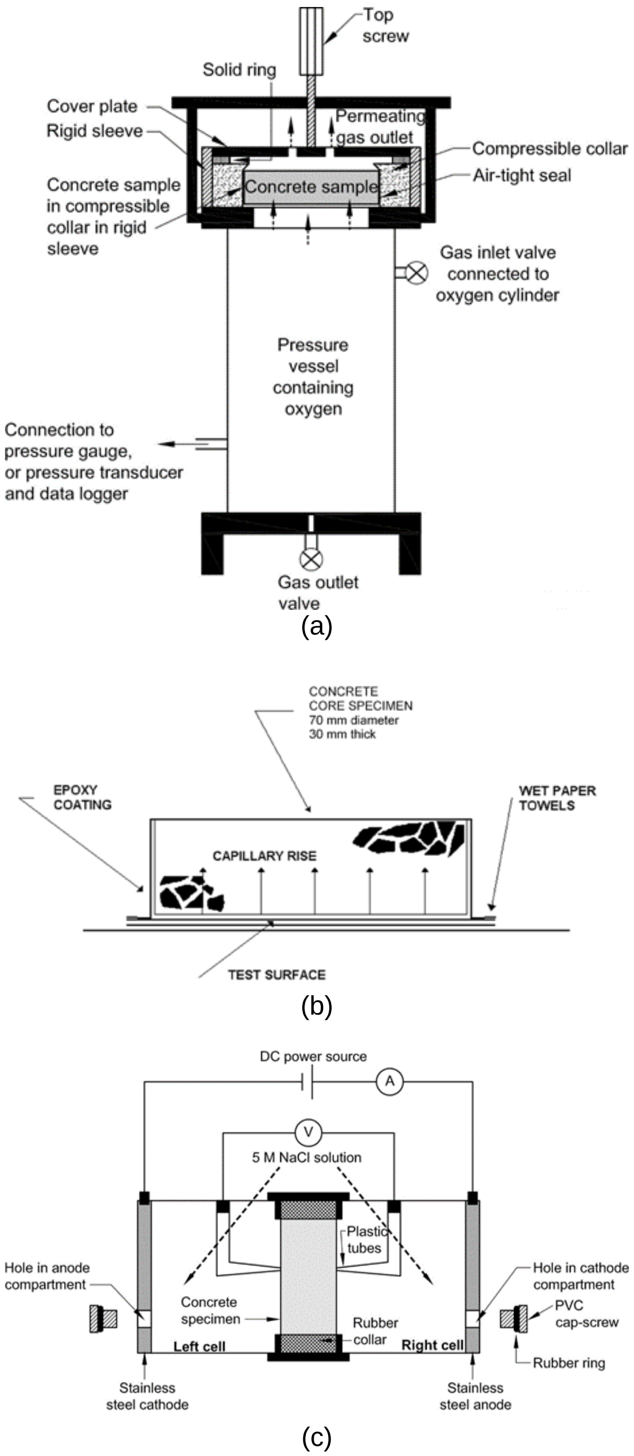


Fig. 2. Three South African durability index tests: (a) falling-head oxygen permeability test; (b) water sorptivity test and (c) chloride conductivity test.

All three tests require that a 70 mm diameter core samples be extracted from the concrete structure being assessed. A surface sample, representing the zone 5 to 35 mm from the exposed surface (i.e. a 30 mm slice), is cut from the core and this slice is then dried in a 50 °C ventilated oven for 7 days. (UCT/WITS, 2017). After completing the oxygen permeability test, the same concrete sample can be used for the water sorptivity test. A different sample is required for the chloride conductivity test.

Ballim (1993a) demonstrated the sensitivity of the oxygen permeability and water sorptivity tests to the important concrete durability parameters such as curing, binder type and water/binder (w/b) ratio. As an example, an adaptation of these results is shown in Fig. 3. The development of these tests for quality control of concrete construction through national specification is discussed in a later section of this paper.

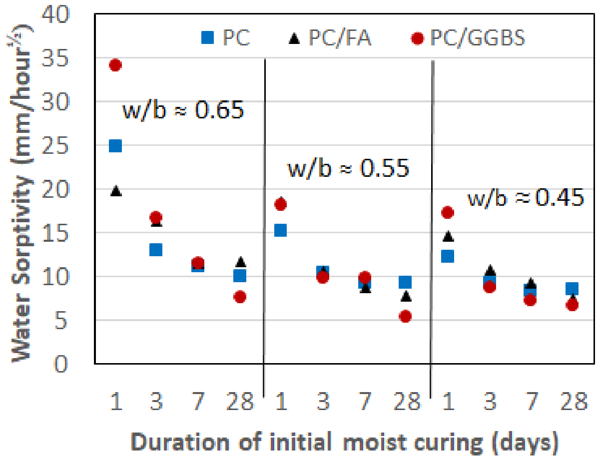


Fig. 3. Sensitivity of the water sorptivity index to variations in initial curing duration, binder type and w/b ratio in concrete (adapted from Ballim, 1993a)

3.2 Correlating the Durability Indexes with Direct Durability Tests

In order to give reliable reference meaning to a durability index test result, the index must be correlated with direct durability testing. This is a particularly difficult process, mainly because it introduces the added complexity of the chemical interaction between the aggressive environment and the compounds in the hydrated cement and concrete. Nevertheless, it is important that such correlations are undertaken even in the face of the very wide variety of chemically aggressive environments to which concrete is subjected, such as chlorides, acids, sulphates and atmospheric carbon dioxide. Local physical and atmospheric conditions such as relative humidity, temperature, wind speed and abrasion add to this complexity and must also be accounted for.

Given the large number of variables and the complexities of their interactions with concrete as a material, we have generally relied on empirical observation under controlled test conditions to provide results that may be correlated to the durability index tests, using numerical models that often are limited in the range of their application.

These limitations usually relate to the characteristics of the concrete materials used and to the geographical region of the aggressive environment studied. This is cumbersome but necessary in order to develop the application of our evolving understanding of concrete technology – but it also means that we should be careful about the regional portability of correlation models indicating the relationships between durability index test results and rates or levels of deterioration caused by a particular aggressive agent.

A further complication in this area of research development is the long time that is required to obtain reliable data of concrete deterioration under natural exposure conditions. This necessarily leads to the need to accelerate the deterioration, usually by controlling the environment of exposure and making it more aggressive to concrete by changing the concentration of one or more of the ionic species in the environment. However, the effects of acceleration are generally not linearly related to concentration and such accelerated tests must also be correlated with the results of natural exposure conditions.

Figure 4 shows an example of such correlation between the water sorptivity index and carbonation depth measured under natural exposure conditions (Ballim, 1996). These results show that the durability index correlates reasonably well with the rate of carbonation and can reproduce the expected relationship of higher carbonation rates for concretes with binders containing supplementary cementitious materials.

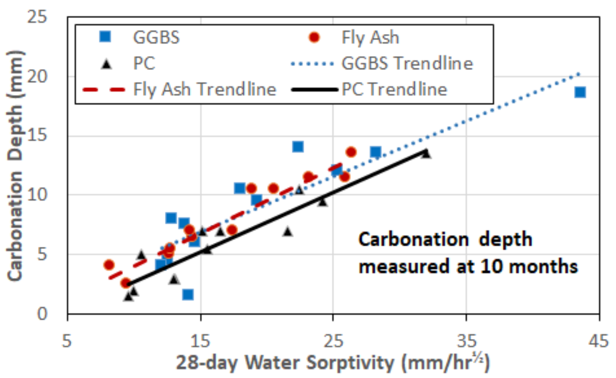


Fig. 4. Correlation between water sorptivity as a durability index and 10-month natural carbonation (Ballim, 1996)

Notably, a later development of the correlation between a durability index and carbonation gave a more fundamental relationship between the permeability coefficient (k) from the oxygen permeability test, and the carbonation diffusion coefficient (Salvoldi *et al.*, 2015). With suitable corrections for carbonatable content of the concrete, this produced a sensible single relationship for a range of concretes with different binders, shown in Fig. 5.

Similarly, Fig. 6 shows the correlation trend developed for chloride conductivity as a durability index, against the chloride diffusion coefficient for concretes made with different binder types and exposed in a natural marine environment. Here again, the durability index measure is able to distinguish the Portland cement concretes as showing higher chloride diffusion rates – and therefore more susceptible to early reinforcement corrosion - than for the blended cement concretes.

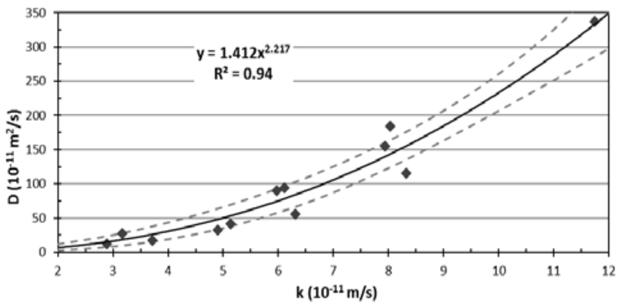


Fig. 5. Permeability (k) vs. effective dry diffusion coefficient (with line of best fit and 95% confidence intervals), range of concretes with various binders (Salvoldi *et al.*, 2015)

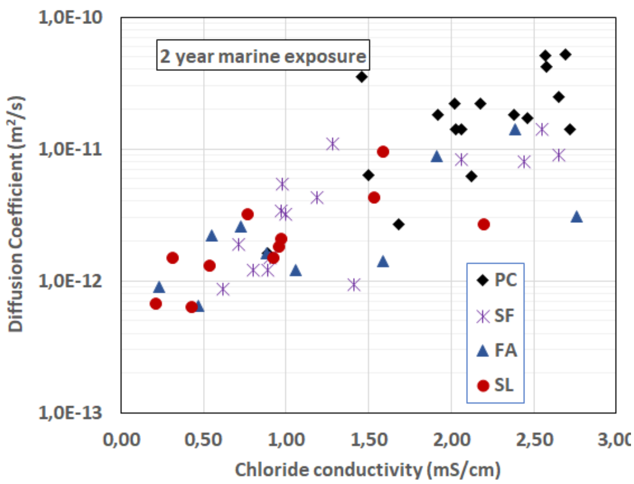


Fig. 6. Correlation between chloride conductivity test results and the measured chloride diffusion coefficient for concretes exposed in a marine environment (adapted from Alexander *et al.*, 1999)

The trends of the data shown in Figs. 4, 5 and 6 are comforting insofar as they show the expected functional relationships between the durability indexes and the deterioration processes, with sufficient sensitivity in the range of measurement. However, the scatter in the data is also important because it points to both the errors in our measurements as well as the shallowness of our understanding of all the influencing variables in the complex process of environmental deterioration of concrete. The problem of the reliability of the trends illustrated in Figs. 4 to 6 is further complicated by the continually evolving and changing cementitious materials that are used in concrete. Each change brings new chemistry and pore structure to the hydrated cement in concrete, and so changes the relationship between the durability index measure and the deterioration process. It is for this reason that developments in service life modelling and durability design must rely on probabilistic approaches with continual iterations of revision and improvement as we become more confident in our understanding of the fundamental aspects that guide deterioration processes in concrete.

3.3 Understanding the Fundamental Mechanisms of Concrete Deterioration

As mentioned above, a coherent approach to developing guidelines for ensuring improved durability of concrete infrastructure must rely on an understanding of the deterioration processes under the range of environments that are aggressive to concrete. The variability of concrete materials, aggressive chemical species and environmental conditions make this a particularly complex and long-term task.

In some instances, normally aggressive ionic species, when present together, act synergistically to change the aggressiveness of the environment. This occurs in the case of concrete exposed to sea water. On its own, the sulphate in sea water would be very aggressive to concrete. However, the presence of chlorides significantly reduces the swelling pressure that could develop in the interaction between the sulphate and the aluminate phases of the cement. On the other hand, the process of carbonation of concrete acts to accelerate the ingress of chloride ions into the concrete when the two processes occur together.

While the concrete research teams in South Africa have undertaken some basic studies on the mechanisms of deterioration (Ballim, 1993b, Alexander and Fourie, 2011), the approach has been to rely on the assistance of colleagues in the basic disciplines – physics, chemistry and materials science – to provide guidance and research in developing our understanding of these aspects.

3.4 Characterising the Aggressiveness of the Environment

Classification of the degree of environmental aggressiveness is essential in developing codes of practice for durability design. Modern design codes generally acknowledge this need for classification and do include categories of aggressiveness as a design input variable. However, we are increasingly realising that the broad environmental classification categories are not sufficiently accurate to give designers the necessary guidance for suitable design responses to aggressiveness. Classifications of the marine zone which are based only on distance from the shoreline do not take account of influencing aspects like wind speed or local topography. Equally, classifications such as ‘indoor’ or ‘outdoor’ exposure of concrete do not sufficiently account for variations in micro-climate or concentrations of the aggressive species.

This has been one of the focus areas of our research work in South Africa in order to properly understand the local and regional variations in the degree of aggressiveness to concrete. Early work in this area considered the degree of aggressiveness of the Johannesburg urban environment to concrete motorway structures in the city (Ballim and Lampacher, 1996). More recently, Alhassan (2014) studied the effects of micro-climate variations on the rate of carbonation of concrete in an inland urban environment. An example of his findings is shown in Fig. 7 which highlights the effects of rain exposure in the outdoor environment in reducing the rate of carbonation in concrete.

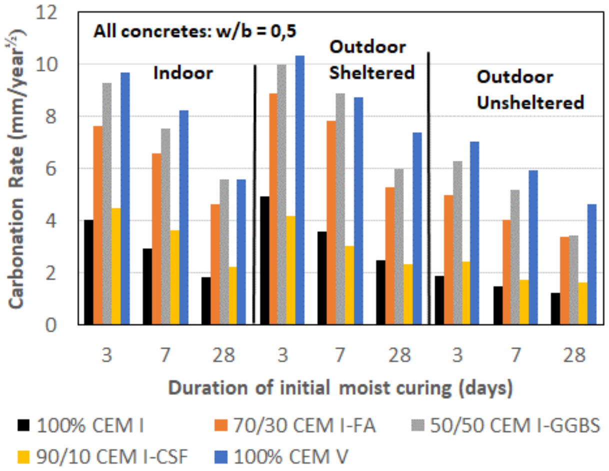


Fig. 7. Effects of micro-climate variations on the rate of carbonation of concretes made with a range of binder types (Alhassan, 2014)

A further example involves chloride environments, where, for South African coastal conditions with characteristic heavy seas and appreciable wave and abrasion load, chloride ingress is significantly deeper into concretes in the tidal wave zone in comparison to a similar zone without such action, such as in protected harbours (Mackechnie and Alexander, 1996).

3.5 Durability Indexes as a Basis for Construction Quality Assurance

The development of reliable durability indexes offers an opportunity for performance-based specifications to control the quality of concrete during construction. This is a significant shift from the “prescriptive-based” specification that relies on imposing limits on aspects like the w/c ratio or binder content, prescribes the binder type to be used in the concrete or the way in which the concrete is to be cured. The durability index presents specifiers with an unambiguous measure of the quality of the concrete – particularly the near-surface zone - after it has been processed and cured by the constructor. A major infrastructure owner in South Africa responsible for road networks has already adopted the durability index approach, and crafted a performance specification around these tests and limiting values.

With this approach to specification, the designer must have a sense of the degree of aggressiveness of the environment of exposure and the appropriate durability index value that will assure suitable quality of the concrete to resist that environmental exposure. This forms the basis for the target performance that the concrete is required to achieve in the durability index test.

Important in this approach is that, within reasoned limits, the constructor is at liberty to choose the method of (say) curing by which the target performance index value is to be achieved. For example, in the context of early-age curing, the durability index test can be used to calibrate the effectiveness of liquid membrane forming curing compounds when compared with different extents of water curing.

While the principle of application of the durability index approach to performance specifications for durability is fairly straightforward, there are a range of issues that must be resolved before the approach is accepted more widely in specifications.

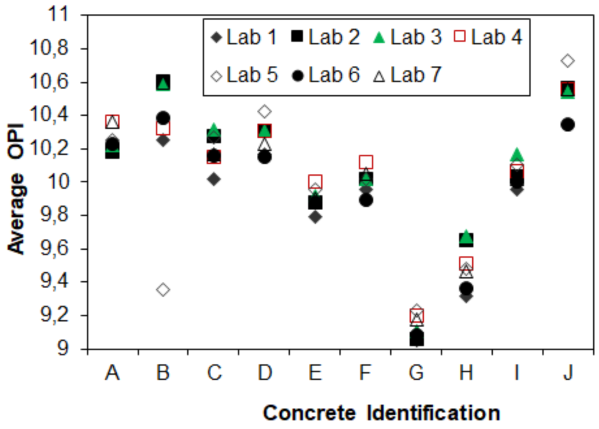
Generally accepted performance limits

The entire concrete sector – owners, designers, constructors and specifying authorities – must agree on performance limits of durability index values in relation to the aggressiveness of the environment of exposure. Our early attempts at specification were unsuccessful because of insufficient consideration of this aspect. Durability index limits were allocated to three categories of concrete quality: "'Poor"; "Good" and "Excellent". Of course, owners of concrete structures wanted "Excellent" concrete and so specified the highest level of performance for all concretes, regardless of the aggressiveness of the environment. A good idea undone by poor choice of terminology and inadequate consultation with all parties.

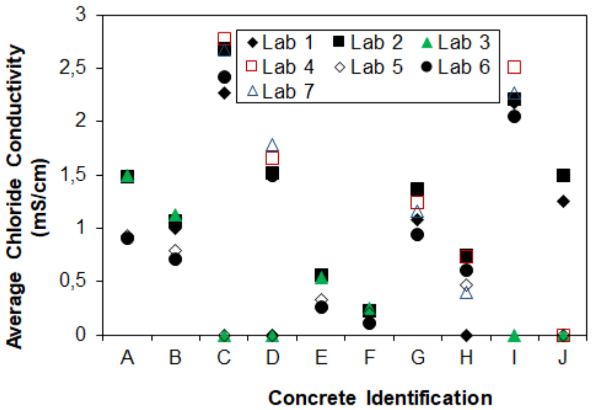
Repeatability and Reproducibility of Index Test Results

All tests are subject to operator and test equipment variability and this aspect must be thoroughly assessed for the durability index tests. Importantly, the repeatability and reproducibility must be properly analysed and openly reported to all parties involved in the concrete sector, who are likely to use the specification. It is also important that users acknowledge the variability and understand how to interpret and respond to such variability.

In the South African experience, several extensive test programmes were undertaken as a joint project between the university-based researchers and our cement and concrete industry partners. Local commercial concrete testing laboratories were encouraged to install the durability test equipment in their laboratories. The design of the equipment was given to them at no cost and, in the early days and where necessary, the research teams assisted in the manufacturing of the equipment. Operators were trained, test samples were prepared at a single laboratory and these were then sent to the different laboratories using a sample identification system unrelated to the composition or processing of the test sample. Figure 8 shows examples of the test results for samples obtained from 10 concretes sent to seven different laboratories, from one particular test programme.



(a)



(b)

Fig. 8. Results of inter-laboratory tests to assess the variability of (a) the oxygen permeability index (OPI) test and (b) the chloride conductivity test (adapted from Stanish, *et al*., 2006)

This experience indicated the need for better training of test operators, further refinements of the test equipment to reduce sensitivity to test conditions and stricter documentation of test procedures. As discussed later, these initiatives significantly improved the acceptance of the test methods and the implementation of performance-based specification for concrete durability in South Africa.

As mentioned above, performance-based specifications using the durability index approach are now in regular use in South Africa, with the tests generally accepted in industry. Two tests – the oxygen permeability and chloride conductivity tests – have the status of national standards as from 2015 (SANS-3001-CO3-1, 2, 3, 2015) while the water sorptivity test method is being prepared as a national standard.

3.6 Durability Index Tests and Service Life Prediction

Increasing confidence in the correlations between the durability index test results and rate of concrete deterioration in natural aggressive environments creates the opportunity for using the measured or specified durability index value as a basis for service life prediction of concrete structures. Figure 9 shows an example of this approach, where the chloride conductivity index test results have been used to predict the time to initiation of reinforcement corrosion in a marine environment. In South Africa, these types of correlations (see also Figs. 4-6 above) have allowed the construction of semi-empirical service life prediction models, which are used where circumstances demand detailed evaluations. However, for more common applications, a set of 'standard design conditions' have been derived that allow the designer to select durability index values for a range of environments and design life periods, that can reasonably be expected to deliver a durable structure (Alexander and Nganga, 2015) (see also Table 1 later).

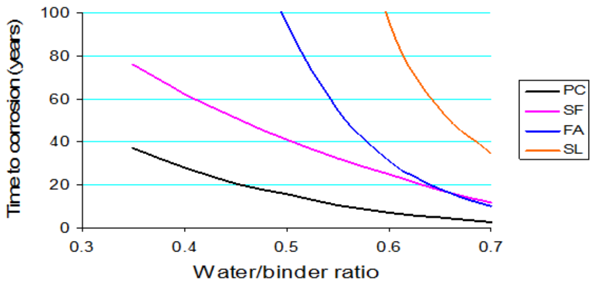


Fig. 9. An example of the use of the chloride conductivity index to predict the time to initiation of corrosion in reinforced concrete with different binder types

3.7 Developing the Approach to Durability Design Based on Durability Indexes

As indicated in the research framework shown in Fig. 1, the reason for coordinating and integrating these different areas of research and development in concrete durability and deterioration studies is to update and improve our approaches to durability design. The general acceptance by the cement and concrete sectors in South Africa of the use of durability index tests in performance specifications for quality assurance of concrete construction, has created the opportunity for extending the idea and using the durability index tests as a basis for durability design. Some progress has been made in this regard and the approach has found early acceptance both in South Africa and in India (Alexander, *et al*., 2005).

Table 1 shows an example of this approach. When read as a table in a possible durability design code, based on the aggressiveness of the environment, the designer is given the freedom to select a suitable cover depth for a given expected service life. The table then provides a maximum chloride conductivity index value (in this case) that will satisfy the requirement for different binder types. The table also provides guidelines on the suitability and practicality of different binder types that are likely to produce a concrete that satisfies the durability index requirement. Once the combination of cover depth and binder type has been selected, the corresponding chloride conductivity value then becomes the basis for establishing the performance-based specification limit for the construction project.

Table 1. An example of a durability design guideline for concrete in a marine environment with an expected corrosion-free service life of 50 years, based on the chloride conductivity index (adapted from Alexander, *et al*., 2005)

Marine Exposure Condition	Cover (mm)	Max 28-d chloride conductivity (mS/cm) for concrete with binder type: 10% CSF	100% PC	30% FA	50% GGBS
Extreme	40	0.25	0.45	0.75	0.85
	60	0.30	0.95	1.35	1.55
	80	0.60	1.30	1.80	2.00
very severe	40	0.35	0.45	0.90	1.10
	60	0.50	1.15	1.75	2.00
	80	0.85	1.65	2.30	2.60
Severe	40	0.55	1.00	1.85	1.95
	60	1.10	1.85	2.95	3.05
	80	1.55	2.50	3.75	3.85

Key:
- (red) Concrete grade > 60 MPa - may be impractical
- (orange) Concrete grade < 30 MPa - not recommended; structural considerations may dominate
- (white) Concrete grade between 30 and 60 MPa; acceptable and practical

4.0 CLOSURE

In this paper, we have presented an integrated framework for research on durability and deterioration of concrete that has guided the work of the research teams working in this area in South Africa for 3 decades. Our starting point was the development of a suite of durability index tests that were aimed at characterising the quality of the near-surface zone of a concrete element. The work has shown that, when the durability indexes are properly correlated to concrete deterioration in natural environments, the indexes become useful as a basis for quality control of concrete construction, service life prediction and guidelines for durability design.

The framework also ensures that there is coherence in the principles that guide our approaches to the separate but complementary areas of research in the broad field of concrete durability studies. This coherence mainly derives from the fact that the framework sees the primary objective of our research efforts as being the need to develop improved approaches to durability design and construction of concrete infrastructure.

We have also tried to highlight the need for substantial further research and development in all of the research domains in the framework. The possibility of more reliable durability index test approaches must continuously be considered and, when properly identified, should replace the existing test methods. Equally, our foundational argument that the durability index should be the basis for an improved approach to durability design must be regularly questioned in the light of new evidence or consideration of alternative approaches that may be more efficient.

Acknowledgement

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